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Wood unscripted potentials:How Can material Deficiencies Become Strengths

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Timber as a material can be defined as a low-density, cellular polymeric composite (…). In terms of its high strength performance and low cost, timber remains the world's most successful fibre composite (Dinwoodie, 2000).

If someone invented wood today it would never be approved as a building material (Lstiburek, 2009).

1. Introduction

1.1. Approaches to wood in construction.

There exists a dichotomy in our approach to wood as building material as indicated by the two quotations above. On the one hand hardly any manmade material can rival wood in terms of its properties, on the other its use causes problems. Wood has lost market shares as a raw material for mass production processes as a result of its individualised characteristics and difficult to predict behaviour. Reaction wood, spiral grain and juvenile wood – present in almost all timbers -- are seen as deficiencies, lowering the material value. This paper sets out to investigate how the wood traits that are commonly seen as shortcomings for construction could be used to bring value to the otherwise inferior material, and what kind of design methods and techniques that entails.

1.2. Wood properties and behaviour.

Wood is an extremely varied material – the physical properties are specie-specific while there exist approximately 30,000 species of trees, its anisotropic behaviour, porosity and heterogeneity reflect the material's complex internal structure (Bodig and Jayne, 1993). The modelling of the mechanical behaviour of timber is further complicated by the fluctuations in material characteristics being dependant on moisture, temperature and time (Wagenführ, 2008). No two pieces of timber are alike, all pieces vary at all structural levels and contain various imperfections that are seen as natural, conversion and seasoning defects (Lyons, 2010).

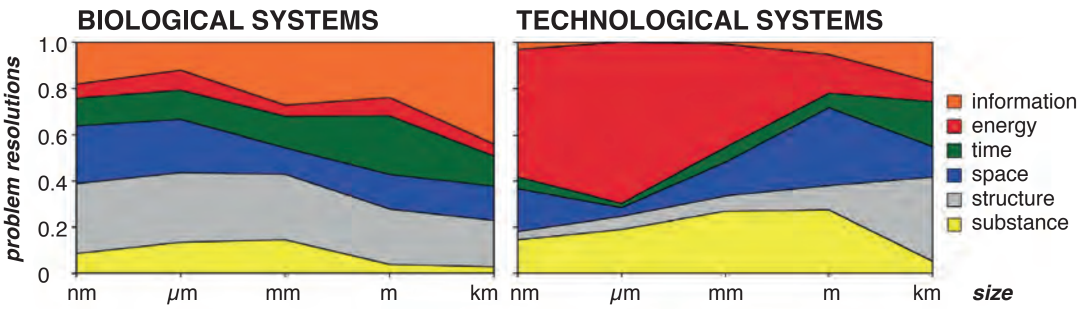
Variation and heterogeneity of timber is seen as a disadvantage in construction: *In the past some of the difficulties could be overcome by selective utilization of certain species and reliance on the larger and older age classes of trees possessing more uniformity. It is now clear, however, that we are no longer able to enjoy such luxuries. More and more trees are characterised by small sizes and greater variability* (Bodig and Jayne, 1993). In order to deal with the heterogeneous characteristics at the scale of mass production two main strategies have been developed. Firstly, manufactured wood products were developed with a goal to offset the problematic effects: *Modern structural composites have minimized and randomized the influences of these naturally occurring defects, but the dimensional* *instability of wood in service remains a definite problem* (Zink-Sharp, 2003). Secondly, understanding wood in engineering is based on simplification, idealisation and statistical average rather than individualised actual characteristics. In continuum mechanics structural analysis timber is considered a homogenous material (Wagenführ, 2008). It is also considered an orthotropic material, that is symmetric about three mutually perpendicular planes (Bodig and Jayne, 1993). These planes are related to the longitudinal, radial and tangential directions in the tree. That assumption implies that the tangential faces are straight and not curved and that the radial faces are parallel and not diverging (Dinwoodie, 2000).

2. Key concepts

The proposed approach to wood architecture is to be based on a set of concepts that form a conceptual framework of the research.

2.1. Systemic and biomimetic stance – the Ju-Jitsu principle.

Frederic Vester (1925-1983), a German biochemist, ecologist and an originator of *networked thinking* that is based on systemic and cybernetic approaches, opposes constructivist against evolutionary types of management. In the former the system is produced at great expense of material and energy, in the latter it emerges spontaneously at little expense. The 4th rule of his eight basic rules of bio-cybernetics outlines the strategy: *exploiting existing forces in accordance with the ju-jitsu principle rather than fighting against them with the boxing method* (Vester, 2007). That in turn resonates with the comparison of biological and technological systems as presented by Julian Vincent, professor of biomimetics at the University of Bath. Vincent argues, that our technology *kills the information* of raw materials, by *reducing, melting, dissolving, homogenising,* thus achieving *random material with no intrinsic information*, further *moulded, casted, turned, joint* with a substantial expense of energy to make the material *ordered with imposed shape and structure* for the final product. Conversely to technological systems, biological systems use information rather than energy to solve technical problems. Information is used to self-assemble structures, that unlike the engineered solutions are hierarchical. Vincent points to our ability to tap abundant and cheap fossil fuels during the Industrial Revolution as a key turning point in our relationship with nature[1].



Comparison of biological effects and engineering TRIZ[2] solutions arranged according to size / hierarchy. Technology uses energy as the primary driver for solving engineering problems across the nanometre to metre scales, with information playing a smaller role. In contrast, biological systems use energy sparingly (about 5% of the cases), relying instead on information and structure. The similarity in solving problems between those two systems is only 12% (Vincent et al., 2006).

[1] Julian Vincent in video interview with Susana Soares JACKMAN, S. 2007. Susana Soares meets Julian Vincent .

[2] a theory of inventive problem solving developed in 1950s Soviet Union

Applying these principles to wood construction means to find solutions based on material self-organisational capacities rather than enforcing form over material. This approach would promote manufacturing and construction techniques that are non-wasteful, less energy consuming and toxic and provide vital alternatives to manufactured wood products in order to overcome the scarcity of good quality and large-dimensional timbers.

Processing a material means energy expenditure and may have an impact on health risks posed by this material, and also on this material's recycling: *The higher the degree of processing, the lower the potential for quick and unproblematic decomposition* (König, 2011).

2.2. Material-orientated design.

The problem of material agency of wood in construction can be tracked back to the 19th century and the rapid development of structural design induced by the introduction of homogenic and isotropic materials – namely iron and later steel. *Iron provided the physical basis for a mathematically oriented formulation of design, thoroughly justified by science* what resulted in a shift of focus to *a more rational, abstract and analytically driven understanding* of construction in structural design (Rinke, 2010). The process of standardisation affected wood construction as well -- the Balloon Frame System based on the 2 x 4 inches module has been introduced in 1830s. Manuel de Landa, Mexican-American artist and philosopher, argues that with the invention of homogenised building materials design has been reduced to a routine and consequently *the linguistically unarticulated knowledge* of craftsmen about complex material behaviour has been disregarded (de Landa, 2001).

Michael Hensel, architect and professor of architecture at the Oslo School of Architecture and Design (AHO), identifies architecture as a domain of *active agency*, where the spatial and material organisation complex is defined as a synthesis of the various scales and their interactions. While in the industrial tradition architects prefer materials that do not exhibit explicit behaviour and are *passive* or in a *stabile equilibrium,* as exemplified by the case of steel and iron, Hensel postulates dynamic condition required by the spatial and material organisation characterised by *active agency*. Wood structure must be understood in relation to environmental conditions affecting its growth. Higher in the organisation system, material behaviour is determined by the material properties and environmental conditions. This in turn has to be harnessed by architectural design, what is the basis of the *instrumentalisation of material behaviour as performative capacity* (Hensel, 2011).

In order to open a new space for design enquiry Achim Menges, professor at the Institute for Computational Design at the University of Stuttgart, envisions the micro scale of the material make-up as a continuum of reciprocal relations with the macro scale of the material systems. Following this approach necessary is understanding and interacting with wood at all scale levels of the material organisation in a holistic manner. Menges identifies computation as a prerequisite to search this space: *computation allows navigating and discovering unknown points within the search space, and thus enables an explanatory design process of unfolding material-specific gestalt and related performative capacity* (Menges and Ahlquist, 2011).

In the abovementioned approaches the process is informed by the capacity of the material systems. That reflects a wider tendency of shifting the interest from structure to material in design and engineering and blurring the distinction between them. Antoine Picon, professor of the History of Architecture and Technology at Harvard Graduate School of Design (GSD) brings an example of the evolution of car bumpers from structural protectors to energy absorbers, that was enabled by the development of energy absorbing composite materials (Picon, 2010). This in turn reflects the biological paradigm where there is no distinction between material and structure.

3. Case studies

3.1. Spiral grain.

First case presents a potential of material self-organisation taking advantage of spiral grain in wood seen by some wood scientists as the most serious single defect in softwoods.

Material deficiencies.

While wood with spiral grain has no abnormal shrinkage, spiral patterns in sawn timber affect the entire length of a piece. Spiral grain in sawn timber combined with change in moisture content causes a warp type called twist. Spiral grain induced twisting in transmission poles can amount to 50^o and break the transmission lines. Additionally the strength in tension, and to a lesser degree in compression, decreases as the slope of the grain in timber increases. Machining and bending of such wood is difficult. For all these reasons spiral grain reduces log value. The actual cost of wood wastage due to spiral grain is difficult to assess, but at times the rejection rate of the crop may amount to 50% (Harris, 1989).

Biological outlook.

Wood structure is highly heterogeneous, with phenomena like reaction wood and spiral growth resulting from the environmental conditions of the tree growth (gravity, wind, sloping site and competition). Spiral growth is a persistent feature for many millions of years, thus unlikely a defect as such would have been eliminated by the evolution. This phenomenon can be observed for most tree species. Studies confirm that spirally grained trees are better suited to meet extreme wind and snow loads (Harris, 1989) as the spiral growth increases stiffness, stability and minimises the use of material in trees (Wagenführ, 2008).

Usage in design and construction.

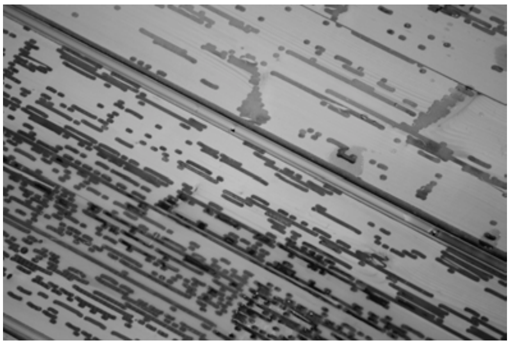
Japanese traditional woodworkers treated the irregularities in grain as an asset to resist certain loads (Brown, 1989). In the Scandinavian boatbuilding tradition *to ensure that the planking in the prow of a boat swept, sloped, in the right direction, it was suitable to choose a clockwise twisted log for the starboard planking, and an anticlockwise twisted log for the port planking* (Säll, 2002). In the 18^{th} and 19^{th} centuries trees with left-hand spiral grain were sought out for the curved moldboard section of the wooden plough. A large hardwood trees with pronounced left-hand spiral grain were greatly prized for the strength of the curved surface. Spirally grained poles also give warning of failure, as they fail progressively by splitting, what makes them favourable for pit-props and mining timbers (Harris, 1989). Andre Wagenführ, professor at the Institute of Wood and Paper Technology (*Institut für Holz- und Papiertechnik*) at the TU Dresden experiments with wood with spiral grain, taking advantage of the interdependence of the fibril angle, stiffness and toughness -- the shallower the slope of the fibrils, the smaller the force required for the deformation of the material (Wagenführ, 2008).

Potential developments.

Image based on a photo by J.A. Kininmost from HARRIS, J. M. 1989. Spiral grain and wave phenomena in wood formation, Berlin, Springer-Verlag.

The photograph depicting a twisted stack of timber as a result of the twist in the same direction in all the individual boards due to spiral grain shows how double-curved shapes can be achieved using minimum energy. Undulation of walls performs acoustically -- causing scattering and attenuation of sound waves, or structurally – providing for self-support. It is proposed to devise design and construction techniques that benefit from the twist phenomenon. Twist is caused by three main factors: (1) annual ring curvature – the closer a stud is sawn to the pith the more prone it is to twist, (2) spiral grain angle – the higher the spiral grain angle the larger the twist, (3) change in moisture content – the drier the studs are the more severe the twist is (Bäckström et al., 2004). That implies that the twist in a piece of timber can be predicted by controlling the way wood is sorted, converted and dried combined with measuring the grain angle. Wood with left-handed spiral grain – particularly prone to twist -- should be sorted out early in the supply chain. Spiral grain angle should be measured using non-invasive technique. There exist several techniques for providing internal cartography of a tree: tracheid effect using a laser beam to map the grain curvature (Grönlund et al., 2007), computed tomography (Sarigul et al., 2003), automated scanner systems, electromagnetic wave scattering (Gjerdrum and Bernabei, 2009), X-ray density measurement, ultrasonic *Sylvatest*, vibration measurement (Ranta-Maunus, 1999). All the methods are already in use or may find industrial application in the near future. Information acquired this way can be used to predict twist during drying (Säll, 2002) and employed in a digital form-finding simulation process to spontaneously achieve forms otherwise difficult and expensive to achieve.

The new *trait-to-form* method would be based on *form-finding* techniques combined with identification of advantages in material characteristics (*trait-finding*). Necessary is development of digital design tools that are orientated towards relationships – between material properties, behaviour, design intents, form and performance, rather than geometry, using simulation as a tool. A prerequisite is feedback from the material. That requires developments in two areas: non-invasive, quick and reliable gradation methods of wood and digital tools capable of simulating behaviour of material systems and allowing for real-time reaction at the manufacturing stage. That would result in reformulation of the linear design-execution process in order to allow for feedback in the workflow. The new integrated workflow should blur the distinction between simulation, design and manufacturing. Interfacing between these stages becomes the biggest challenge in the integrated process.



Digitized Grain*, Hironori Yoshida, 2013 -- a research project based on *an integrated process, being a modern translation of how craftsman reads characteristics of natural materials and dynamically reflects on fabrication processes. (…) For the automated production process, the material features are digitally scanned, image-processed and translated into motion paths for a seven-axis industrial robotic arm. This sequence of operations are executed by an algorithm and then transmitted to any kind of cnc machine that operates following the inputs generated by the program. The program can flexibly change the amount of tooling and resolutions of image processing. Text and photograph: http://www.caad.arch.ethz.ch/blog/scan-to-production/

3.2. Juvenile wood.

Second case investigates the potential of using juvenile wood, commonly present in the product of forest thinning that represents substantial part of the annual crop of timber, reportedly 50% in the case of the UK (Ross et al., 2009).

Material deficiencies.

Juvenile wood is considered inferior in quality to normal wood, unsuitable for construction, composite panels, high-grade paper, and not competitive as a source of energy (Ranta-Maunus, 1999, Shmulsky and Jones, 2011). Roundwood is not commonly used in the developed countries as a structural material due to the lack of design guidelines and readily available and reliable connectors, unavailability of the material through normal commercial channels, the difficulty when attaching cladding to irregular and round structure (Ranta-Maunus, 1999, Dickson et al., 2011).

Biological outlook.

Juvenile wood strength is up to 50% lower due to low density resulting from thin cell wall layers, shorter cells and high microfibril angle. That angle affects directional shrinkage as well. The longitudinal shrinkage from green to oven dry amounts to 2%, while the average value for other wood is negligible and does not exceed 0.2%. This may cause radial cracking as the juvenile and other wood is usually present alongside and is not sharply delineated but gradually vary from ring to ring (Shmulsky and Jones, 2011).

Advantages of roundwood thinnings.

Embodied energy of roundwood thinning material is 40% lower than of sawn lumber (Dickson et al., 2011). Further, the material self-replenishes over a much shorter period of time than that needed for sawn timber. The cost of debarked round timber is roughly a half of sawn timber while the characteristic bending strength of unsorted material may be even double the value of sawn timber (Ranta-Maunus, 1999).

Usage in design and construction.

Small diameter roundwood, a counterpart of thinnings, has been widely used for centuries -- mostly for their convenience in size and where quality was of secondary importance -- in such structures as sheds, barns or fencing. Recently 50 m span domes of small diameter roundwood have been shown to be fully feasible. 27 m high Observation Tower at Apeldoorn (architect Pieter Huybers; 1995) has been built of 2.5 and 3.6 m long and 12,15 and 20 cm in diameter debarked larch poles. The projects employ a design strategy based on three-dimensional space frames where short length and small cross-section of the poles are not a disadvantage, and using the whole cross-section additionally offsets the problem of weakness (Ranta-Maunus, 1999).


The Hooke Park Workshop, design Richard Burton of ABK and Frei Otto, engineers Buro Happold, 1989. Photographs http://www.aaschool.ac.uk/.

The workshop building Hooke Park in Dorset (Richard Burton, Frei Otto and Buro Happold, 1988) was an experimentally constructed gridshell using round (65-180 mm diameter) green Norwegian spruce thinnings achieving a 15 metres span (Davey, 2009, Romer, 2011). Richard Kroeker, a Canadian architect pursuing ecological sustainability, designed a series of buildings made of small diameter roundwood thinnings based on Native American architecture and boatbuilding. The indigenous assembly is a spring-loaded, stressed skin structure composed of lightweight and locally sourced parts. While none of the components has sufficient strength, together in a tensioned assembly they become structurally sound. The design process takes place in real time with reference to the behavioural limits of the material, the anticipated use and performance. To achieve curvilinear, efficient forms, wood is worked when it is green and flexible (Kroeker, 2013).

Pictou Landing Health Centre in Nova Scotia, architects Brian Lilley, Richard Kroeker, Peter Henry. Photograph R. Kroeker, from KROEKER, R. 2013. Lernen vor der Architektur der indigenen Volke Amerkas. Learning from Native American Architecture. *Detail,* 5.

Potential developments.

In silviculture the initial narrow spacing and later thinning strategy – necessary for improving the growth rate and wood quality -- makes the remaining trees twice as expensive as planting to a wider spacing, unless there was a commercial market for the thinned material (Shmulsky and Jones, 2011). A market study by the Technical Research Centre of Finland indicates the potential markets for thinnings in the development of small buildings as well as large engineered structures, which could be attractive when combined with unique architecture, especially in the leisure industry (Ranta-Maunus, 1999). A departure point for developing new techniques is research into material systems based on inferior in quality, short and small section components, where structural strength is derived from the combination of material behaviour and geometry.

While juvenile wood strength achieves about half the value of normal wood, its lower modulus of elasticity allows for bending it beyond the proportional limit, and even more so in green condition. Bending strength of round timber is higher than that of sawn timber of similar cross-section size, and small cross-sections are known to have relatively higher strength than large ones based on the Weibull theory (Ranta-Maunus, 1999). Processing thinnings into sawn timber causes problems, due to imbalance of stresses leading to deformities and cracks and low yield due to the conical geometry of the logs (Dickson et al., 2011). Even though high temperature drying can minimise cracking during drying, the bending strength of high-temperature dried logs is about 10% lower than of seasoned logs (Ranta-Maunus, 1999) and there are difficulties with effective kiln-drying roundwood timber above 75 mm diameter (Ross et al., 2009). The logical consequence then is to develop material and construction systems using roundwood logs in the green condition, harnessing the properties and behaviour of this particular material. As the presented examples demonstrate, it is possible to synergise various phenomena thus achieving wide spans, quick construction times, structures effective in terms of form compactness and weight to strength ratio at low cost and using obsolete materials.

The key aspect becomes than the identification of synergies within the organisation of material and construction systems. Architectural design has the potential to bridge the gaps between different levels of the hierarchical organization -- from the *nano* scale of wood internal structure affecting its behaviour to the *mega* scale of the world forestry. That is only possible through trans-disciplinary cooperation and systemic outlook.

4. Conclusions

The volume of wood commonly seen as defective is difficult to estimate, but it may be in the extent of 50% of the crop. It is proposed that architectural design plays a key role in finding applications for such wood by informing its methods by bio-cybernetics and biomimetics. In order to handle the challenge a new properties-led, integrated and continuous design and production process is proposed. The *trait-to-form* process is to be based on bottom-up emergence and self-organisation developed by feedback from the material in relation to the top-down constraints: particular design intent and environment. Key aspects of the *trait-to-form* process are: (1) identification of synergies within the systems of forestry, material characteristics and architectural tectonics, (2) focus in design on relationships between material properties, behaviour, design intents, form, tectonics and performance, (3) inclusion of real-time material feedback in the continuous design and production process, (4) incorporation of material system behaviour simulation in the digital design toolkit, (4) development of tectonic systems deriving strength from combination of material characteristics and geometry.

The proposed framework has a potential to address the environmental and economical problems at the same time contributing to the field of architectural design, and therefore it is intended to develop that methodology further.

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